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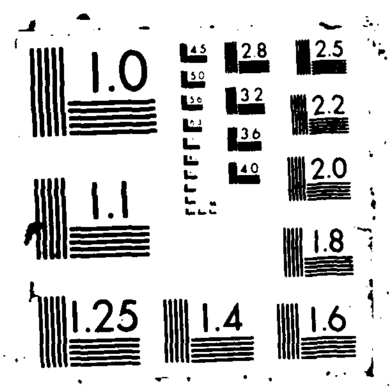
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Progress on eight research problems addressing distributed tactical decisionmaking is described.

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NAVAL C^3 DISTRIBUTED TACTICAL DECISION MAKING

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July 31, 1987

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NAVAL C^3 DISTRIBUTED TACTICAL DECISIONMAKING

1. PROJECT OBJECTIVES

The objective of the research is to address analytical and computational issues that arise in the modeling, analysis and design of distributed tactical decisionmaking. The research plan has been organized into two highly interrelated research areas:

(a) Distributed Tactical Decision Processes;
(b) Distributed Organization Design.

The focus of the first area is the development of methodologies, models, theories and algorithms directed toward the derivation of superior tactical decision, coordination, and communication strategies of distributed agents in fixed organizational structures. The framework for this research is normative.

The focus of the second area is the development of a quantitative methodology for the evaluation and comparison of alternative organizational structures or architectures. The organizations considered consist of human decisionmakers with bounded rationality who are supported by C^3 systems. The organizations function in a hostile environment where the tempo of operations is fast; consequently, the organizations must be able to respond to events in a timely manner. The framework for this research is descriptive.

2. STATEMENT OF WORK

The research program has been organized into seven technical tasks -- four that address primarily the theme of distributed tactical decision processes and three that address the design of distributed organizations. An eighth task addresses the integration of the results. They are:

2.1 Real Time Situation Assessment: Static hypothesis testing, the effect of human constraints and the impact of asynchronous processing on situation assessment tasks will be explored.

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2.2 Real Time Resource Allocation: Specific research topics include the use of algebraic structures for distributed decision problems, aggregate solution techniques and coordination.

2.3 Impact of Informational Discrepancy: The effect on distributed decisionmaking of different tactical information being available to different decisionmakers will be explored. The development of an agent model, the modeling of disagreement, and the formulation of coordination strategies to minimize disagreement are specific research issues within this task.

2.4 Constrained Distributed Problem Solving: The agent model will be extended to reflect human decisionmaking limitations such as specialization, limited decision authority, and limited local computational resources. Goal decomposition models will be introduced to derive local agent optimization criteria. This research will be focused on the formulation of optimization problems and their solution.

2.5 Evaluation of Alternative Organizational Architectures: This task will address analytical and computational issues that arise in the construction of the generalized performance-workload locus. This locus is used to describe the performance characteristics of a decisionmaking organization and the workload of individual decisionmakers.

2.6 Asynchronous Protocols: The use of asynchronous protocols in improving the timeliness of the organization's response is the main objective of this task. The tradeoff between timeliness and other performance measures will be investigated.

2.7 Information Support Structures: In this task, the effect of the C^3 system on organizational performance and on the decisionmaker's workload will be studied.

2.8 Integration of Results: A final, eighth task, is included in which the various analytical and computational results will be interpreted in the context of organizational bounded rationality.

3. STATUS REPORT

In the context of the first seven tasks outlined in Section 2, a number of specific research problems have been formulated and are being addressed by graduate research assistants under the supervision of project faculty and staff. Research problems which were completed prior to or were not active during this last quarter have not been included in the report.

3.1 DISTRIBUTED TEAM HYPOTHESIS TESTING WITH EXPENSIVE COMMUNICATIONS

Background: In Command-Control-and-Communication (C3) systems multiple hypothesis testing problems abound in the surveillance area. Targets must be detected and their attributes must be established; this involves target discrimination and identification. Some target attributes, such as location, are best observed by sensors such as radar. More uncertain target locations are obtained by passive sensors, such as sonar or IR sensors. However, target identity information requires other types of sensors (such as ESM receivers, IR signature analysis, human intelligence etc). As a consequence in order to accurate locate and identify a specific target out of a possibly large potential population (including false targets) one must design a detection and discrimination system which involves the fuzing of information from several different sensors generating possibly specialized information about the target. These sensors may be collocated on a platform (say a ship in a Naval battle group) and be physically dispersed as well (ESM receivers exist in every ship, aircraft, and submarine). The communication of information among this diverse sensor family may be difficult (because of EMCON restrictions) and is vulnerable to enemy countermeasure actions (physical destruction and jamming). It is this class of problems that motivates our research agenda.

Research Goals: We are conducting research on distributed multiple hypothesis testing using several decision-makers, and teams of decision-makers, with distinct private information and limited communications. The goal of this research is to *unify* our previous research in situation assessment, distributed hypothesis testing, and impact of informational discrepancy; and to *extend* the methodology, mathematical theory and computational algorithms so that we can synthesize and study more complex organizational structures. The solution of this class of basic

research problems will have impact in structuring the distributed architectures necessary for the detection, discrimination, identification and classification of attributes of several targets (or events) by a collection of distinct sensors (or dispersed human observers).

The objective of the distributed organization will be the resolution of several possible hypotheses based on many uncertain measurements. Each hypothesis will be characterized by several attributes. Each attribute will have a different *degree of observability* to different decision makers or teams of decision makers; in this manner, we shall model different specialization expertise associated with the detection and resolution of different phenomena. Since each hypothesis will have several attributes, it follows that in order to reliably confirm or reject a particular hypothesis, two or more decision-makers (or two or more *teams* of decision-makers) will have to pool and fuze their knowledge.

Extensive and unecessary communication among the decision-makers will be discouraged by explicitly assigning costs to certain types of communication. In this manner, we shall seek to understand and isolate which communications are truly vital in the organizational performance; the very problem formulation will discourage communications whose impact upon performance is minimal. Quantitative tradeoffs will be sought.

We stress that we shall strive to design distributed organizational architectures in which teams of teams of decision-makers interact. For example, a team may consist of a *primary* decision-maker together with a *consulting* decision-maker -- the paradigm used by Papastavrou and Athans.

The methodology that we plan to employ will be mathematical in nature. To the extent possible we shall formulate the problems as mathematical optimization problems. Thus, we seek *normative solution concepts*. To the extent that human *bounded rationality* constraints are available, these will be incorporated in the mathematical problem formulation. In this case, the nature of the results will correspond to what is commonly refered to as *normative/descriptive* solutions. Therefore, we visualize a dual benefit of our basic research results. From a purely mathematical point of view, the research will yield nontrivial advances to the distributed hypothesis-testing problem; an extraordinary difficult problem from a mathematical point of view. From a psychological perspective, we hope that the normative results will suggest

counterintuitive behavioral patterns of -- even perfectly rational -- decision- makers operating in a distributed tactical decision-making environment; these will set the stage for designing empirical studies and experiments and point to key variables that should be observed, recorded and analyzed by cognitive scientists. From a military C3 viewpoint, the results will be useful in structuring distributed architectures for the surveillance function.

Progress during the past quarter: In the past quarter we focused our attention to the problem of *ternary* hypothesis testing by a team of two cooperating decision makers; communication between the two decision-makers is costly and consists of a finite alphabet. The problem is to distinguish among three different hypotheses. Each decision-maker obtains an uncertain measurement of the true hypothesis. The so-called *primary* decision-maker has the option of making the final team decision or consulting, at a cost, the *consulting* decision-maker. The consulting decision-maker is constrained to provide information using a ternary alphabet. The team objective is to minimize the probability of error together with the communications cost (if any).

This seemingly simple distributed decision problem turns out to have an extraordinarily complex structure. We have been able to characterize the nature of the optimal solution; we also were able to obtain a significant insight into the complexity of its solution. We obtained the necessary equations and are analyzing them.

Many more mathematical models and approaches remain to be developed. This research will most probably form the core of the Ph.D. research of J. Papastavrou under the supervision of Professor Athans.

Documentation: None as yet.

3.2 DISTRIBUTED HYPOTHESIS TESTING WITH MANY AGENTS

Background: The goal of this research project is to develop a better understanding of the nature of the optimal messages to be transmitted to a central command station (or fusion center) by a set of agents who receive different information on their environment. In particular, we are interested in solutions of this problem which are tractable from the computational point of view. Progress

in this direction has been made by studying the case of a large number of agents. Normative/prescriptive solutions are sought.

Problem Statement: Let H_0 and H_1 be two alternative hypotheses on the state of the environment and let there be N agents (sensors) who possess some stochastic information related to the state of the environment. In particular, we assume that each agent i observes a random variable y_i with known conditional distribution $P(y_i|H_j)$, j = 0, 1, given either hypothesis. We assume that all agents have information of the same quality, that is, the random variables are identically distributed. Each agent transmits a binary message to a central fusion center, based on his information y_i. The fusion center then takes into account all messages it has received to declare hypothesis H_0 or H_1 true. The problem consists of determining the optimal strategies of the agents as far as their choice of message is concerned. THis problem has been long recognized as a prototype problem in team decision theory: It is simple enough so that analysis may be feasible, but also rich enough to allow nontrivial insights into optimal team decision making under uncertainty.

Results: This being studied by Prof. J. Tsitsiklis and a graduate student, Mr. George Polychronopoulos. Under the assumption that the random variables y_i are conditionally independent (given either hypothesis), it is known that each agent should choose his message based on a likelihood ratio test. Nevertheless, we have constructed examples which show that even though there is a perfect symmetry in the problem, it is optimal to have different agents use different thresholds in their likelihood ratio tests. This is an unfortunate situation, because it severely complicates the numerical solution of the problem (that is, the explicit computation of the threshold of each agent). Still, we have shown that in the limit, as the number of agents becomes large, it is asymptotically optimal to have each agent use the same threshold. Furthermore, there is a simple effective computational procedure for evaluating this single optimal threshold.

We have also shown that if each agent is to transmit K-valued, as opposed to binary messages, then still each agent should use the same decision rule, when the number of agents is large. Unfortunately, however, the computation of this particular decision rule becomes increasingly

broader as K increases.

We have investigated the case of M-ary ($M > 2$) hypothesis testing and constructed examples showing that it is better to have different agents use different decision rules, even in the limit as $N \to \infty$. Nevertheless, we have shown that the optimal set of decision rules is not completely arbitrary. In particular, it is optimal to partitition the set of agents into at most $M(M-1)/2$ groups and, for each group, each agent should use the same decision rule. The decision rule corresponding to each group and the proportion of the agents assigned to each group may be determined by solving a linear programming problem, at least in the case where the set of possible observations by each agent is finite.

In more recent work, the following have been accomplished.

(a) We studied the Neyman-Pearson (as opposed to Bayenian) version of the problem, in the case of M=2 hypothesis. The asymptotically optimal solution has been found and involves the Kullback-Liebler information distance.

(b) We considered a class of symmetic detection problems in which given any hypothesis H_i, each sensor has probability ε of making an observation indicating that some other hypothesis H_j is true. A simple numerical procedure has been found which completely solves this problem. Furthermore, a closed form formula for the optimal decision rules has been found for the case where the "noise intensity" ε is very small.

We also conducted research which address the issue of the validity of asymptotic considerations when the number of agents N is moderate ($N \approx 5$).

Documentation

[1] J. N. Tsitsiklis, "On Threshold Rules in Decentralized Detection," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986; also LIDS-P-1570, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, June 1986.

[2] J. N. Tsitsiklis, "Decentralized Detection by a Large Number of Sensors," LIDS-P-1662,

April 1987; Submitted to *Mathematics of Control, Signals and Systems*.

3.3 COMMUNICATION REQUIREMENTS OF DIVISIONALIZED ORGANIZATIONS

Background: In typical organizations, the overall performance cannot be evaluated simply in terms of the performance of each subdivision, as there may be nontrivial coupling effects between distinct subdivisions. These couplings have to be taken explicitly into account; one way of doing so is to assign to the decisionmaker associated with the operation of each division a cost function which reflects the coupling of his own division with the remaining divisions. Still, there is some freedom in such a procedure: For any two divisions A and B it may be the responsibility of either decisionmaker A or decisionmaker B to ensure that the interaction does not deteriorate the performance of the organization. Of course, the decisionmaker in charge of those interactions needs to be informed about the actions of the other decisionmaker. This leads to the following problem. Given a divisionalized organization and an associated organizational cost function, assign cost functions to each division of the organization so that the following two goals are met: a) the costs due to the interaction between different divisions are fully accounted for by the subcosts of each division; b) the communication interface requirements between different divisions are small. In order to assess the communication requirements of a particular assignment of costs to divisions, we take the view that the decisionmakers may be modeled as boundedly rational individuals, that their decisionmaking process consists of a sequence of adjustments of their decisions in a direction of decreasing costs, while exchanging their tentative decisions with other decisionmakers who have an interest in those decisions. We then require that there are enough communications so that this iterative process converges to an organizationally optimal set of decisions.

Problem Statement: Consider an organization with N divisions and an associated cost function $J(x_1,\ldots,x_N)$, where x_i is the set of decisions taken at the i-th division. Alternatively, x_i may be viewed as the mode of operation of the i-th division. The objective is to have the organization operating at a set of decisions $(X_1,\ldots,x_N)$ which are globally optimal, in the sense that they minimize the organizational cost J. We associate with each division a decisionmaker DM_i, who

is in charge of adjusting the decision unables x_i. We model the decisionmakers as "boundedly rational" individuals; mathematically, this is translated to the assumption that each decisionmaker will slowly and iteratively adjust his decisions in a direction which reduces the organizational costs. Furthermore, each decisionmaker does so based only on partial knowledge of the organizational cost, together with messages received from other decisionmakers.

Consider a partition $J(x_1,\ldots,x_N) = \sum_{i=1}^{N} J^i(x_1,\ldots,x_N)$ of the organizational cost. Each subcost J^i reflects the cost incurred to the i-th division and in principle should depend primarily on x_i and only on a few of the remaining x_j's. We then postulate that the decisionmakers adjust their decisions by means of the following process (algorithm):

(a) DM_i keeps a vector x with his estimates of the current decision x_k of the other decisionmakers; also a vector λ with estimates of $\lambda_i^k = \partial J^k/\partial x_i$, for $k \neq i$. (Notice that this partial derivative may be interpreted as DM_i's perception of how his decisions affect the costs incurred to the other divisions.

(b) Once in a while DMi updates his decision using the rule $x_i := x_i = \sum_{k=1}^{N} \lambda_i^k$, ($\gamma$ is a small positive scalar) which is just the usual gradient algorithm.

(c) Once in a while DM_i transmit his current decision to other decisionmakers.

(d) Other decisionmakers reply to DM_i, by sending an updated value of the partial derivative $\partial J^k/\partial x_i$.

It is not hard to see that for the above procedure to work it is not necessary that all DM's communicate to each other. In particular, if the subcost J_i depends only on x_i, for i, there would be no need for any communication whatsoever. The required communications are in fact determined by the sparsity structure of the Hessian matrix of the subcost functions J_i. Recall now that all that is given is the original cost function J; we therefore, have freedom in choosing

the J_i's and we should be able to do this in a way that introduces minimal communication requirements; that is, we want to minimize the number of pairs of decisionmakers who need to communicate to each other.

The above problem is a prototype organizational design problem and we expect that it will lead to reasonable insights in good organizational structures. On the technical side, it may involve techniques and tools from graph theory. Once the above problem is understood and solved, the next step is to analyze communication requirements quantitatively. In particular, a distributed gradient algorithm such as the one introduced above converges only if the communication (between pairs of DM's who need to communicate) is frequent enough. We will then investigate the required frequencies of communication as a function of the strenght of coupling between different divisions.

Progress to Date: A graduatre student, C. Lee, supervised Prof. J. Tsitsiklis, has undertaken the task of task of formulating the problem of finding partitions that minimize the number of pairs of DM's who need to communicate to each other as the topic of his SM research. It was realized that with a naive formulation the optimal allocation of responsibilities, imposing minimal communication requirements, corresponds to the centralization of authority. Thus, in order to obtain more realistic and meaningful problems we are incorporating a constraint requiring that not agent should be overloaded. A number of results have been obtained for a class of combinatorial problems, corresponding to the problem of optimal organizational design, under limited communications. In particular certain special cases were solved and other special cases have been successfully reformulated as linear network flow of assignment problems, for which efficient algorithms are know. As simulation study is underway to validate the hypothesis that better task allocation results into better convergence.

Documentation: The Master's thesis of Mr. C. Lee will be ready by August 1987.

3.4 COMMUNICATION COMPLEXITY OF DISTRIBUTED CONVEX OPTIMIZATION

Background: The objective of this research effort is to quantify the minimal amount of information that has to be exchanged in an organization, subject to the requirement that a certain

goal is accomplished, such as the minimization of an organizational cost function. The problem becomes interesting and relevant under the assumption that no member of the organization "knows" the entire function being minimized, but rather each agent has knowledge of only a piece of the cost function. A normative/prescriptive solution is sought.

Problem Formulation: Let f and g be convex function of n variables. Suppose that each one of two agents (or decisionmakes) knows the function f (respectively g) , in the sense that he is able to compute instantly any quantities associated with this function. The two agents are to exchange a number of binary messages until they are able to determine a point x such that $f(g) + g(x)$ comes within ε of the minimum of $f+g$, where ε is some prespecified accuracy. The objective is to determine the minimum number of such messages that have to be exchanged, as a function of ε and to determine communication protocols which use no more messages than the minimum amount required.

Results: The problem is being studied by Professor John Tsitsiklis and a graduate student, Zhi-Quan Luo. We have shown that a least $0(n\log 1/\varepsilon)$ messages are needed and a suitable approximate and distributed implementation of ellispsoid-type algorithms work with $0(n^2\log^2 1/\varepsilon)$ messages. The challenge is to close this gap. This has been accomplished for the case of one-dimensional problem $n=1$, for which it has been shown that $0(\log 1/\varepsilon)$ messages are also sufficient. More recently, we have succeeded in generalizing the technique employed in the one-dimensional case, and we obtained an algorithm which is optimal, as far as the dependence of ε is concerned. The question of the dependence of the amount of communications on the dimension of the problem ($0(n)$ versus $0(n^2)$) seems to be a lot harder and, at present, there are no available techniques for handling it.

An interesting qualitative feature of the communication-optimal algorithms discovered thus far is the following: It is optimal to transmit aggregate information (the most significant bits of the gradient of the function optimized) in the beginning; then, as the optimum is approached more refined information should be transfered. This very intuitive result seems to correspond to

realistic situtations in human decisionmaking. Another problem which is currently being investigated concerns the case where are $K > 2$ decisionmakers cooperating for the minimization of $F_1 + ... + f_k$ where each f_i is again a convex function.

This problem turns out to be very hard, but some progress has been made on a simpler version of the problem. Namely, we considered the problem of evaluating a simple function (say the sume of K numbers) by a hierarchy (tree) of decisionmakers and tight bounds have been obtained on the required amount of communication.

Documentation:

[1] J. N. Tsitsiklis and Z.-Q. Luo, "Communication Complexity of Convex Optimization," LIDS-P-1617, Laboratory for Information and Decision Systems, MIT,October 1986; *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December, 1986; This paper has been submitted to the *Journal of Complexity*; also an invited talk was given at the *2nd Symposium on Complexity of Approximately Solved Problems*, Columbia University, New York, April 1987.

3.5 DISTRIBUTED ORGANIZATION DESIGN

Background: The bounded rationality of human decisionmakers and the complexities of the tasks they must perform mandate the formation of organizations. Organizational architectures distribute the decisionmaking workload among the members: different architectures impose different individual loads and result in different organizational performance. Two measures of organizational performance are accuracy and timeliness. The first measure of performance addresses in part the quality of the organization's response. The second measure reflects the fact that in tactical decisionmaking *when* a response is generated is also significant: the ability of an organization to carry out tasks in a timely manner is a determinant factor of effectiveness.

The scope of work was divided into three tasks:

(a) Evaluation of Alternative Organizational Architectures;
(b) Asynchronous Protocols; and
(c) Information Support Structures.

During this year, the research effort has been organized around three foci. In the first one, we continue to work on the development of analytical and algorithmic tools for the analysis and design of organizations. In the second, the focus is integration of the results obtained thus far through the development of a workstation for the design and analysis of alternative organizational architectures. Finally, the experimental program was initiated last year with the objective of collecting data necessary to calibrate the models and evaluate different architectures for distributed decisionmaking has been continuing and is expanding.

3.5.1 Design and Evaluation of Alternative Organizational Architectures.

In order to design an organization that meets some performance requirements, we need to be able to do the following:

(a) Articulate the requirements in qualitative and quantitative terms;
(b) Generate candidate architectures that meet some of the requirements;
(c) Evaluate the candidate organizations with respect to the remaining requirements;
(d) Modify the designs so as to improve the effectiveness of the organization;

The generalized Performance Workload locus has been used as the means for expressing both the requirements that the organization designer must meet and the performance characteristics of any specific design. Consider an organization with N decisionmakers. Then the Performance Workload space is an N+2 dimensional space in which two of the dimensions correspond to the measures of the organization's performance (say, accuracy and timeliness) and the remaining N dimensions correspond to the measure of the workload of each individual decisionmaker. Two loci can be defined. First, the Requirements locus is the set of points in this N+2 dimensional space that satisfy the performance and workload requirements associated with the task to be performed by the organization. The second, the System locus, is the set of points that are achievable by a particular design. The design problem can then be conceptualized as the reshaping and repositioning of the System locus in the Performance Workload space so that the requirements are met.

Several thesis projects were continued during this period. The individual problem statements and a decription of the progress to date follow:

Generation of Flexible Organizational Structures

Problem Statement: Develop a methodology for modeling and analyzing classes of variable-structure organizations, i.e., organizations where the interactions between decision makers can change. This study is limited, however, to organizations in which their topology changes as a function of the tasks they perform. This constitutes another step towards the representation of more realistic human decisionmaking organizations.

The first objective is a precise definition of a variable-structure organization. Trade-offs exist indeed between the complexity of the mathematical description, the modeling power of the representation, and the limitations due to the computational implementation. The second objective is the explanation of results to be obtained from the comparison of the performance of organizations with variable structure and of the performance of organizations with fixed structure.

Progress to Date: This problem is being addressed by Jean-Marc Monguillet under the supervision of Dr. A. H. Levis. The focus of the research effort has been on the understanding of the meaning of the terms "architecture", "flexibility", "reconfigurability" and "variability", and on the identification of the appropriate mathematical tools for the description of variable architectures.

Since information processing occurs asynchronously and concurrently in these organizations, the Petri Net formalism is a convenient tool for modeling these systems. However, the Ordinary Petri Nets cannot take into account the changes in the connections between nodes. Their grammar has to be extended.

The Colored Petri Net formalism seemed to be the appropriate extension to be used. It allows to color the different possible structures of the organization and the incoming tokens (i.e., the tasks) which correspond to them. This leads to the representation of the organization as layers of

structures. The formalism also allows changes in colors and interconnections of the structures. Unfortunately, when the number of colors is too large, the representation becomes extremely complicated, and cannot be represented graphically. This reason has lead us to investigate the properties of nets of higher level, namely the Predicate-Transition Nets.

In Predicate-Transition Nets, the tokens, instead of being colored items following colored paths, are specific values of variables. They are the arguments of predicates associated with the places, and of logical formulas built in the transitions, which decide where the tokens will be directed in the firing process. These nets are therefore very appropriate for the treatment of organizational structures with changing properties and relations. Besides, the graphical representation they give is much clearer than in the other formalisms.

The modeling of a three member variable-structure organization carrying out an air defense task (AAW) with scarce weapon resources will be investigated. Each decisionmaker (DM) has his internal structure represented by the four-stage model. This allows to differentiate the kind of interactions that two different decisionmakers may have between them. Depending on the threat, which can be of several types, the interactions between DM's differ.

The research effort is focused on developing the Predicate Transition Net of an organization with variable structure that subsumes the ordinary Petri Net model of organizations with fixed structure. Then, the computation of performance measures of organizations modeled by Predicate-Transition Nets will be sought, starting with the AAW example. The objective is to compare the performance (Workload, Timeliness and Accuracy) of an organization with a variable structure and a comparable one with a fixed structure.

Documentation: None yet.

Design of Organizations

Objective: Given a feasible organizational architecture, develop a methodology for (a) identifying the functions that must be performed by the organization in order that the task be accomplished, (b) selecting the resources (human, hardware, software) that are required to implement these

functions, and (c) integrating these resources - through interactions - so that the system operates effectively.

Progress to Date: This research problem is being investigated by Stamos K. Andreadakis under the supervision of Dr. A. H. Levis. The design methodology has been modified in order to address the following formulation of the design problem of decisionmaking organizations: Given a mission, design the DM organization that is accurate, timely, exhibits a task processing rate that is higher than the task arrival rate and whose decisionmakers are not overloaded. The design requirements explicitly stated are:

The accuracy J must be greater than a threshold J_0 or, equivalently, that the expected cost J be less than the threshold J_0:

$$J < J_0 \qquad [1]$$

The timeliness measure T be less than a threshold T_0:

$$T < T_0 \qquad [2]$$

The task processing rate R be greater than the task arrival rate R_0:

$$R > R_0 \qquad [3]$$

The constraints that must be observed are: each decisionmaker must not be overloaded, i.e., a decisionmakers' information processing rate F be less than the rationality threshold F_0:

$$F < F_0 \qquad [4]$$

During this past quarter, a classification of data flow structures has been introduced and a procedure to generate structures has been developed. The methodology has been refined and has been subdivided into four phases. The candidate structure generation is the first phase of the four phase design methodology which is presented in the sequel.

Design methodology:

The design methodology has four phases (FIgure 1): in phase 1 a data flow structure generator produces a set of candidate data flow structure designs, from which a few representative data flow structures are selected. In phase 2 the activity of the functions, the accuracy, the processing time and the processing rate of each data flow structure are computed. In phase 3, each data flow structure is augmented and transformed into a C^2 organization; The functions are allocated to decisionmakers and the communication protocols are designed. In phase 4 the evaluation of the measures of performance of each C^2 organiztion is performed and then the respective measures of effectiveness are computed.

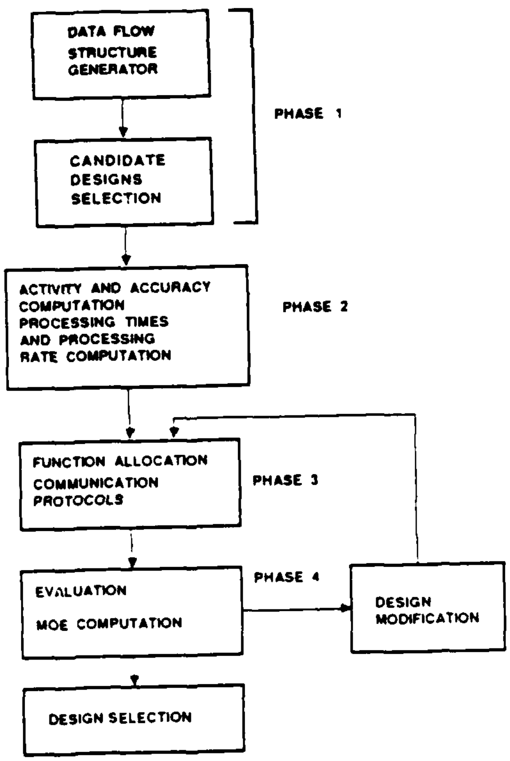


Figure 1. Design Methodology Flowchart

The designs are modified to increase the measure of effectiveness by introducing decision aids, changing the functyion allocation, or modifying the protocols. The introduction of the hardware, i.e., the specifications for the required decision aids and databases as well as for the communications links (the command and control systems) transforms each decision-making organziation into the corresponding command and control organization.

Finally a command and control organization is selected from the candidate designs on the basis of the greatest MOE value.

Phase 1: Data flow structure generation

The Petri Net formalism is used to represent the data flow structures. The processing stages are represented by transitions, whereas the data or information that are input or output of the processing stages are represented by places. The availability of data or information at specific places of the Petri Net is represented by the existence of tokens in the respective places.

In order to describe the information processing, the following processing stages are introduced: Initial processing [IP]: this stage receives data from the sensors and performs preliminary situation assessment. Data fusion [DF]: this stage receives and combines [fuses] the results of IP. Middle processing [MP]: this stage follows the DF stage and performs situation assessment. Results fusion [RF]: this stage combines the results of several MP stages. Final processing [FP]: this stage operates on the outcome of the RF stage and effectively selects a response - produces an output.

Interactions between stages

In order to design a data flow structure, the permissible interactions among processing stages must be established. These are:

IP -> DF or IP -> RF
DF -> MP or DF -> FP
MP -> RF
RF -> FP

It should be noted that more than one IP nodes can be connected to one DF node (RF node) and more than one MP nodes can be connected to one RF node, whereas exactly one MP node can follow each DF node and exactly one FP node can follow each RF node (DF node).

Thus the permissible information flow types are:

IP -> DF -> MP -> RF -> FP flow type 1
IP -> DF -> FP flow type 2
IP -> RF -> FP flow type 3

Classification of data flow structures

The classsification is performed on the basis of the data flow types that are combined in the data flow structure, i.e., the permissible interactions that are present in the data flow structure. By combination of two of more flows, the existence of the corresponding types of data flow in the structure is implied. The feasible combinations and the corresponding classes thus defined are:

pure flow type 1: class 1
pure flow type 2: class 2
pure flow type 3: class 3
combination of flow type 1 and flow type 2: class 12
combination of flow type 1 and flow type 3: class 13 [indistinguishable from 12]
combination of flow type 1, flow type 2, and flow type 3: class 123

Combination of flow type 2, and flow type 3 is not feasible. Given a class and the number of inputs, the data flow structures of the class are characterized by two parameters: the degree of complexity and the degree of redundancy.

Degree of complexity of a data fusion [DF] node (or results fusion [RF] node) is the number of initial processing [IP] nodes (middle processing [MP] nodes) that are connected to the fusion node. The term complexity is justified by the observation that the more data that are fed to a data fusion [DF] node, the more complex the middle processing [MP] is. Similar considerations

apply to the results fusion [RF] and final processing [FP] nodes.

Degree of complexity of the DF stage (or RF stage) is the maximum of the degree of complexity of the individual DF (RF) nodes.

Degree of redundancy of an initial processing [IP] node (or middle processing [MP] node) is the number of data fusion [DF] nodes (result fusion [RF] nodes) that receive data (results) from the same initial processing IP (middle processing MP) node. The term redundancy is justified by the observation that the same information is communicated to more than one processing paths of the data flow structure.

Degree of redundancy of the DF stage (or RF stage) is the maximum of the degrees of redundancy of the individual IP (MP) nodes corresponding to the DF (RF) stage.

If the structure has both data fusion and results fusion stages, two degrees of complexity and two degrees of redundancy are required to characterize the structure.

In order to generate candidate data flow structures from each class, the range of the degree of complexity and the range of the degree of redundancy for the DF and RF stages must be specified. These are selected by considering the adaptability of the data processing functions required by the task to the processing schema represented by the data flow structure, as well as the minimum connectivity requirements to meet survivability.

Once these ranges (c_{df1}, c_{df2}, (r_{df1}, r_{df2}), (c_{rf1},c_{rf2}) and (r_{rf1}, r_{rf2}), have been selected, all structures with

$$r_{df1} \leq r_{df} \leq r_{df2}$$

$$c_{df1} \leq c_{df} \leq c_{df2}$$

$$r_{rf1} \leq r_{rf} \leq r_{rf2}$$

and

$$c_{rf1} \le c_{rf} \le c_{rf2}$$

are generated.

Having selected the representative data flow structures, the design proceeds with Phase 2 which computes the MOPs of the data flow structures.

Phase 2: MOPs computation for the data flow structures

The objectives of the second phase are to compute the total activity and thus the processing time of each function, the accuracy of the response and an estimate of the processing rate range of the data flow structure. In order to compute these quantities, the algorithms that implement the data processing must be developed, and be implemented in software.

The computation of total activity of the functions is based on Information Theory. In order to compute the activity of the functions, the entropy of the variables of the algorithms that implement the functions must be computed. Hence the histograms of these variables must be obtained. This computation is performed by simulating the decisionmaking process and keeping track of the values obtained by the variables and their respective frequency.

At the same time the accuracy of the response is computed. Then a representative values F_0 of the processing rate of the human decisionmaker is selected and the processing time T_i of function i is computed.

$$T_i = G_i/F_0$$

The processing times thus obtained are subsequently used in the computation of the response time of the organization, the timeliness measure(s) and the processing rate. Therefore, the workload constraints will be satisfied because the C^2 organizations that will be developed from these data flow structures have been designed so that enough time is allowed for the

decisionmakers to execute their assigned tasks.

Next an estimate of the processing rate range is computed as follows: The processing rate r_i of transition i is:

$$r_i = F_0/G_i$$

Assuming that each transition is assigned to a different decisionmaker, the maximum processing rate of the data flow structure is equal to the minimum of the processing rates of the individual transitions. Information flow paths are the paths on the Petri Net that emanate from the input and terminate at the output. The processing time along each information flow path is the sum of the processing times of the transitions that belong to the path. The inverse of the maximum of the processing times of the information flow paths is the minimum processing rate of the data flow structure . The processing rate range thus obtained is only an estimate of the processing rate range of the Decisionmaking organization, since it does not take into account the delays along the communication links that will be introduced in Phase 3.

If the task arrival rate is less than the minimum processing rate, the C^2 organization that will be designed from the data flow structure is likely to satisfy the processing rate requirement. If the task arrival rate is greater than the maximum processing rate, multiple processing channels, which are copies of the basic data flow structure must be introduced, so that the arriving tasks can be assigned to alternate channels of the C^2 organization.

·Phase 3: Transformation of data flow structures into C^2 organizations

In Phase 3, each candidate data flow structure is augmented and is transofrmed into a decisionmaking organization. During this phase, functions are allocated to the decisionmakers, the required communication processes are introduced and represented by transitions on the Petri Net, and finally the protocols for information exchange among decisionmakers are selected [synchronous vs asynchronous].

Function allocation: Functions allocated to a decisionmaker must be observe 3 requirements: (1) must be related through an input-output relationship, i.e., the output of one function must be the input to the next function performed by the decisionmaker so that each decisionmaker processes information relevant to the same subtask. (2) must belong to different time zones on the Petri Net so that they observe concurrency and (3) must conform to the specialization of the respective decisionmaker. Requirements 1 and 2 are satisfied by function that are on the same information flow path; thus only functions that belong to the same information flow path are considered for allocation to a decisionmaker. When such a set of functions is allocated to a decisionmaker, a resource place is introduced, that is connected so that it is an output place of the last and an input place of the first transition allocated to the decisionmaker.

Phase 4: MOPs and MOE evaluation for the C^2 organizations

In Phase 4 the computation of the measures of performance of the candidate decisionmaking organization designs is performed. Specifically the Accuracy J, Timeliness T and processing rate R are computed. Then the Measure of Effectiveness of each design is computed. The Measure of Effectiveness is defined in the decision strategy space as the ratio of the number of decision strategies that satisfy the requirements to the total number of decision strategies. If the MOE is not satisfactory, iterations are performed to modify the design so that the MOE value is increased. The modifications may include alternative function allocation, introduction of decision aids and databases and changing the communication protocols.

Finally the design having the highest MOE values is selected.

The methodology tackles the design problem at two levels: the data flow structure level and the decisionmaking organization level. The importance of this differentiation is the ability to generate and classify structures parameterized by the complexity and redundancy of the information processing, without considering the particulars of the decisionmaking organization. After the generation of the candidate data flow structures, the methodology addresses the allocation of funtctions to organization members and the selection of hardware.

In this respect, the methodology is a flexible top-down approach to the design problem, that

results in the expansion of the set of candidate architectures. Another benefit from the top-down approach is that the requirements and specifications for decision aids, databases and communications equipment are derived through the objective evaluation of the effectiveness of the C2 organization, as opposed to the abstract a priori specification of their characteristics as in the case of a bottom-top approach.

Finally the distinction between the data flow structure and the decisionmaking organization design, introduces two opportunities for the fine-tuning of the C^2 organization: one at the data flow level and one at the decisionmaker and hardware level.

Documentation:

[1] A. H. Levis and S.K. Andreadakis, "Computer-Aided Analysis of Organizations," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[2] S.K. Andreadakis and A. H. Levis, "Accuracy and Timeliness in Decision-Making Organizations," *Proc. 10th IFAC World Congress*, July 27-31, 1987, Munich, FRG and *Proc. 9th MIT/ONR Workshop on C^3 Systems,* LIDS-R-1624, MIT Cambridge, MA. December 1986.

[3] S. K. Andreadakis and A. H. Levis, "Design Methodology for Decision-Making Organizations," *Proc. of C^3 Symposium*, June 1987, Washington DC.

Performance Evaluation of Organizations with Decision Aids

Problem Statement:: Analyze and evaluate the impact of decision support systems (DSS) on the effectiveness of decisionmaking and information processing organizations. In particular, investigate the case of teams of decisionmakers assisted by decision support systems.

Progress to Date: This work is being done by Jean-Louis Grevet under the supervision of Dr. A. H. Levis. The concept of team of decisionmakers has been clarified. A team of decisionmakers is defined as being an organization in which the members:

- have a common goal
- have the same interests and same beliefs.

- have activities which must be coordinated so that they achieve a higher performance.

Thus, for a task X with probability distribution p(X) and a cost function c(X) for the organization, one condition for the organization to be a team is that its members have the same perception of the task $p_T(X)$ and assign the same cost to each input $c_T(X)$. The team will account perfectly for the organizational objectives when:

$$p_T(X) = p(X) \text{ and } c_T(X) = c(X)$$

A generic model of a decisionmaker assisted by a decision support system has been proposed. It accounts for the fact that most real systems contain both elements of centralization and decentralization, i.e. the users can share certain resources - centralized databases or mainframes - and access individually other facilities such as intelligent terminals.

The impact of the decision support system on the overall decisionmaking process will be assessed. It is characterized by the fact that it modifies the strategy of each decisionmaker who must now integrate in his choices the possibility of requesting information from the DSS. Thus, each decisionmaker has three alternatives vis-à-vis the DSS:

- he can ignore it and process the information by himself.
- he can query it and rely totally on the response.
- he can query it and compare the response to his own perception of the issue.

These choices are consistent with the analysis carried out by Scott Weingaertner and reported earlier.

The result for the organization is that the DSS:
- can increase its effectiveness by providing accurate responses in a more timely manner and by decreasing the activity of each of its members.
- can improve its cohesiveness by supplying the same responses to different members who might have divergent perception of the task.

On the other hand, characteristics of the DSS such as its transmission reliability or its interface usability can affect the organization's effectiveness, if they degrade. In the same way, if the DSS provides information which is not consistent with the organizational objectives, it can lead to a degradation of performance. It is thus important to integrate in the team of decisionmakers a well-designed decision support system.

Documentation: No formal documentation yet. A thesis proposal has been written in order to define the relevant issues and the goals of the study.

3.5.2 Computer Aided Evaluation of System Architectures

During the last few years, a number of problems regarding distributed tactical decisionmaking have been addressed and models, algorithms, and methods have resulted that are useful for answering specific aspects of the overall problem. In order to integrate these results into a consistent methodology and to provide the means for designing an experimental program, a computer aided design system has been developed. While the primary support for this development has been by the Basic Research Group (BRG) of the Technical Panel on C^3 of the Joint Directors of Laboratories, there has been sufficient contribution by the staff of this project to warrant its inclusion in this report. The components of the system contributed by this project are identified by "DTDM support" in the detailed description that follows.

The design workstation has been named **CAESAR** for **C**omputer **A**ided **E**valuation of **S**ystem **AR**chitectures. It consists of four major components:

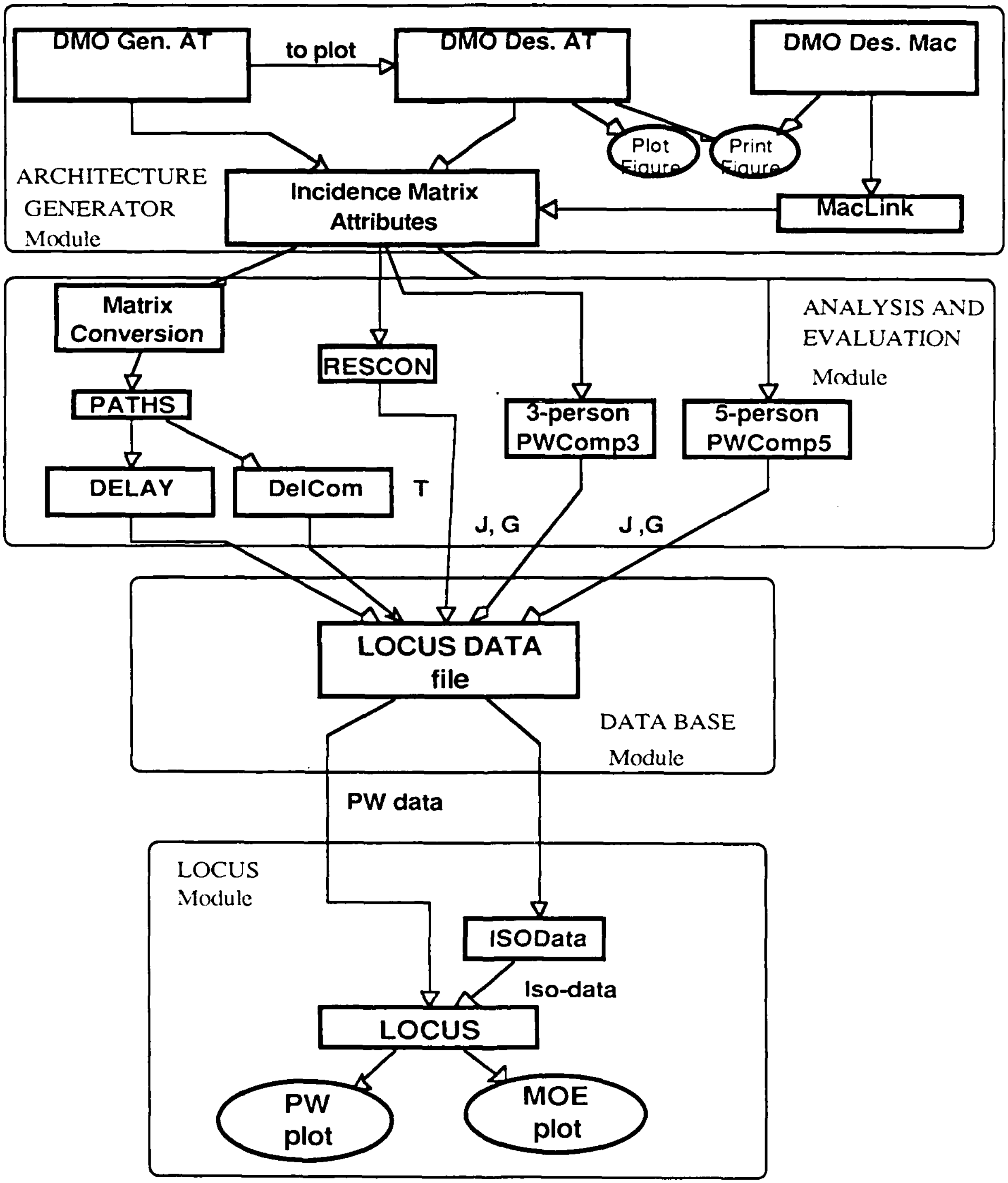
The **Architecture Generator** which constructs feasible organizational forms using Petri Nets.

The **Analysis and Evaluation Module** which contains many of the algorithms for the computation of the Measures of Performance.

A **Data Base** which is used to store the results of the analysis.

The **Locus Module** that constructs the generalized Performance Workload locus of an organization and can be used to evaluate Measures of Effectiveness.

The structure of the software system is shown in Figure 1. V. Jin and J. Azzola, under the supervision of Dr. A. H. Levis, have been continuing work in completing the modules and integrating the software. The descriptions of the modules that follow have been revised to reflect the current status.



CAESAR: Computer - Aided Evaluation of System ARchitectures v. 1.0. 3/87

LIST OF MODULES IN CAESAR

A. ARCHITECTURE GENERATOR

DMO Gen.AT

Program that generates the Petri Nets of Decisionmaking Organizations that satisfy a set of structural constraints, as well as constraints imposed by the user. The algorithm is based on P. Remy's thesis (1986) and has been implemented in DOS 3.0 © IBM, using Turbo Pascal 3.01A ©Borland International and Screen Sculptor ©Software Bottling Company.
Status: Program operational. It requires an interface with DMO Des.AT so that a graphical description of the feasible architectures can be obtained directly. (DTDM support)

DMO Des.AT

Interactive graphics program for the construction of the Petri Nets of arbitrary organizational architectures. It can be used to create and store subsytems and to combine them to form large organizational structures. Program, developed by I. Kyratzoglou, also creates the analytical description of the Petri Nets. Implemented in DOS 3.0, Professional Fortran, Graphics Tool Kit, and Graphic Kernel System, all ©IBM.
Status: To be completed by August 31. Documentation completed. (JDL support).

DMO Des.Mac

Interactive graphics program for the construction of the Petri Nets of arbitrary organizations. It can be used to design organizations of arbitrary size through the use of nested subnets. Program developed for the Apple Macintosh by the Meta Software Corp. using the Design Open Architecture System ©Meta Software Corp. The program creates the analytical description of the Petri Net, as well as store functions and attributes represented by the transitions, places, and connectors. Program continues to be enhanced by J. L. Grevet and L. Jandura to be consistent with analytical description of Petri Nets used in various algorithms.
Status: Program operational. (JDL support)

MacLink ©Dataviz

Commercial software for for converting and transmitting files between the DOS machines and the Macintosh.
Status: MacLink has been installed and is operational: it can transfer the data structure of a Petri Net from the DMO Des.Mac module to the Analysis and Evaluation Module.

Incidence Matrix / Attributes	Standard form for the data structure of Petri Nets. The files contain the incidence matrix or flow matrix of the Petri Net and the attributes and functions associated with the elements of the net. **Status:** Standard version of incidence matrix has been implemented; the specifications for the attribute file have also been developed and implemented. Program Operational. (DTDM support)

B. ANALYSIS AND EVALUATION MODULE

Matrix Conversion	Simple algorithm that transforms the incidence matrix into the interconnection matrix used in Jin's algorithm. Algorithm in Turbo Pascal 3.01A. **Status:** Algorithm developed by Jin is operational. (DTDM support)
Paths	Algorithm developed by Jin in her thesis that determines all the simple paths and then constructs the concurrent paths in an organizational architecture. This is an efficient algorithm that obtains the answers by scanning the interconnection matrix.Algorithm in Turbo Pascal 3.01A. **Status:** Program is operational. (DTDM support)
Delay	Simple algorithm that calculates path delays and expected delay when processing delays are constant. Algorithm in Turbo Pascal 3.01A. **Status:** Algorithm is operational. (DTDM support)
Del Com	Algorithm developed by Andreadakis that calculates measures of timeliness when the processing delays are described by beta distributions. It also accounts for the presence of jamming and its effect on timeliness. Algorithm in Turbo Pascal 3.01A. **Status:** Problem specific version operational; general version to be completed by September 1. (DTDM support)
Res Con	Algorithm developed by Hillion in his thesis that calculates the maximun throughput in a Timed Event Graph, a special class of Petri Nets. It also detrmines the optimal schedule in the presence of resource and time constraints. The procedure incorporates an algorithm proposed by Martinez and Silva for determining simple

paths through the calculation of s-invariants.
Status: Independent version of algorithm revised by D. Perdu is operational; integrated version in workstation to be operational by August 1. (JDL support)

PW Comp 3

Algorithm for the computation of a three-person organization's performance measure J (Accuracy) and the workload of each one of the decisionmakers. The algorithm computes the accuracy of the response and the workload for each admissible decision strategy. This version was developed by Andreadakis in Turbo Pascal.
Status: Program is operational. (DTDM support)

PW Comp 5

A variant of PW Comp 3, but for a five-person organization modeling the ship control party of a submarine. Algorithm developed by Weingaertner as part of his thesis. Implemented in Turbo Pascal.
Status: Program is operational.

C. DATA BASE MODULE

LOCUS Data File

Data file in which the results from the evaluation of a decisionmaking organization are stored. The file, as currently structured, can accommodate five measures of performance - accuracy, timeliness, and workload for three persons. It also contains four indices that specify the decision strategy associated with each record.
Status: Three-person organization version operational. General structure operational. (JDL support)

D. LOCUS MODULE

LOCUS

Graphics plotting program that generates two or three dimensional loci or two- and three-dimensional projections of higher dimensional loci. This is the basic program used to construct the Performance - Workload locus of an organization. Basic version developed by Andreadakis and Bohner and described in latter's thesis.
Status: Version using professional graphics controller is operational. Revised transportable version adhering to the VDI standard and with improved user interface is also operational. The VDI version is operational for organizations with up to five decisionmakers (DTDM support)

ISO Data

Algorithm for obtaining some measures of effectiveness from the measures of performance stored in the Locus

Data file. Specifically, it finds isoquants: e. g., locus of constant accuracy, or constant workload.
Status: New version for microcomputers being implemented by J. Azzola. Preliminary version operational; some output device problems to be resolved.

E. INPUT / OUTPUT

Output: By adopting the Virtual Device Interface (VDI) standard and the Enhanced Graphics standard, it is possible to develop a version of the CAESAR software that is transportable to other IBM PC ATs or compatibles and to drive a wide variety of output devices: various monitors, printers, laser printers, and pen plotters. Output to monitor, and pen plotter operational.

Input: A uniform user interface with windowing capability is needed to make the system useable by analysts and designers. Commercially available software are being investigated to select the most appropriate one. Expected completion date is September 1.

We still expect to have the transportable version of CAESAR operational by September 1, 1987 and demonstarate it at the next annual review of the DTDM program.

3.5.3 Design of Experiments

A major application of CAESAR is in the design and analysis of experiments in which different organizational forms will be evaluated. At this time, V. Jin has initiated a project, under the supervision of Dr. A. H. Levis, in which she is assessing the applicability of certain methodologies in the physical sciences for the design of experiments to the behavioral sciences. In the meantime, with funding from Joint Directors of Laboratories, an experiment has been carried out to determine the stability of the bounded rationality constraint and to obtain values for it. A technical paper has been written and a full separate technical report is expected by September 1.

Documentation:

[1] A. C. Louvet, J. T. Casey, A. H. Levis, "Experimental Investigation of the Bounded Rationality Constraint" *Proc. of C^3 Symposium*, June 1987, Washington, DC.

5. RESEARCH PERSONNEL

Prof. Michael Athans,	Co-principal investigator
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Prof. John Tsitsiklis,	
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Mr. Jason Papastavrou	graduate research assistant (Ph.D)
Ms. Chongwan Lee	graduate research assistant (M.S.)
Mr. Jean-Louis Grevet	graduate research assistant (M.S.)
Mr. Jean-Marc Monguillet	graduate research assistant (M.S.)

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[2] G. J. Bejjani, "Information Storage and Access in Decisionmaking Organizations," MS Thesis, Technology and Policy Program, also, Report LIDS-TH-1434, Laboratory for Information and Decision Systems, MIT, January 1985.

[3] Y. V.-Y. Jin, "Delays for Distributed Decisionmaking Organizations," MS Thesis, Mechanical Engineering, also, Report LIDS-TH-1459, Laboratory for Information and Decision Systems, MIT, May 1985.

[4] K. L. Boettcher, "A Methodology for the Analysis and Design of Human Information Processing Organizations," Ph.D., Thesis, Dept. of Electrical Engineering and Computer Sciences, also, Report LIDS-TH-1501, Laboratory for Information and Decision Systems, MIT, September 1985.

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[9] P. A. Remy, "On the Generation of Organizational Architectures Using Petri Nets," MS Thesis, Technology and Policy Program, also, Report LIDS-TH--1630, Laboratory for Information and Decision Systems, MIT, December 1986.

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[1] R. P. Wiley and R. R. Tenney, "Performance Evaluation of Stochastic Timed Decision-Free Petri Nets," *Proc. 24th IEEE Conference on Decision and Control.* December 11-13, 1985, Ft. Lauderdale, FL, pp. 558-563.

[2] G. J. Bejjani and A. H. Levis, "Information Storage and Access in Decisionmaking Organizations," LIDS-P-1466, Laboratory for Information and Decision Systems, MIT, May 1986.

[3] J. N. Tsitsiklis and M. Athans, "On the Complexity of Decentralized Decisionmaking and Detection Problems, *IEEE Trans. on Automatic Control*, Vol. AC-30, No. 5, May 1985.

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[11] J. Tsitsiklis, "On Optimal Thresholds in Decentralized Detection," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[12] A. H. Levis and S. K. Andreadakis, "Computer-Aided Design of Organizations," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[13] P. Remy , A. H. Levis, V. Jin, "On the Design of Distributed Organizational Structures," LIDS-P-1581, Laboratory for Information and Decision Systems, MIT, July 1986, *Proc. 10th IFAC World Congress*, Munich, FRG, July 1987.

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[20] H. P. Hillion and A. H. Levis, "Performance Evaluation of Decisionmaking Organziations," *Proc. of C^3 Symposium*, Washington DC, June 1987.

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